



# Measurement of the $t\bar{t}$ production cross section in pp collisions at $\sqrt{s} = 8$ TeV in dilepton final states containing one $\tau$ lepton



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## ABSTRACT

The top-quark pair production cross section is measured in final states with one electron or muon and one hadronically decaying  $\tau$  lepton from the process  $t\bar{t} \rightarrow (\ell\nu_\ell)(\tau\nu_\tau)b\bar{b}$ , where  $\ell = e, \mu$ . The data sample corresponds to an integrated luminosity of  $19.6 \text{ fb}^{-1}$  collected with the CMS detector in proton–proton collisions at  $\sqrt{s} = 8$  TeV. The measured cross section  $\sigma_{t\bar{t}} = 257 \pm 3 \text{ (stat)} \pm 24 \text{ (syst)} \pm 7 \text{ (lumi) pb}$ , assuming a top-quark mass of 172.5 GeV, is consistent with the standard model prediction.

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## 1. Introduction

Top quarks at the CERN LHC are mostly produced in pairs with the subsequent decays  $t\bar{t} \rightarrow W^+bW^-\bar{b}$ . The decay modes of the two W bosons determine the event signature. The dilepton decay channel corresponds to the case in which both W bosons decay into leptons, where the term lepton usually refers to electrons or muons, as studied in Refs. [1,2]. In this letter we measure the production cross section of top-quark pairs by considering dilepton decays where one W boson promptly decays into  $\ell\nu_\ell$ , with  $\ell = e$  or  $\mu$ , and the other decays into  $\tau\nu_\tau$ ,  $t\bar{t} \rightarrow (\ell\nu_\ell)(\tau\nu_\tau)b\bar{b}$ . The expected fraction of these events is 4/81 of all  $t\bar{t}$  decays. The  $\tau$  lepton is identified by means of its hadronic decay products, with a branching fraction  $\mathcal{B}(\tau \rightarrow \text{hadrons} + \nu_\tau) \simeq 65\%$ , to produce a narrow jet with a small number of charged hadrons, denoted as  $\tau_h$ . The cross section is measured by counting the number of  $\ell\tau_h + X$  events consistent with originating from  $t\bar{t}$  production, after subtracting the contributions from other processes, and correcting for the efficiency of the event selection. A similar method was used in pp collisions at a centre-of-mass energy of  $\sqrt{s} = 7$  TeV [3]. This “ $\tau$  dilepton” channel is of particular interest because it is a natural background process to the search for a charged Higgs boson [4,5] with a mass smaller than that of the top quark. In this case, the production chain  $t\bar{t} \rightarrow H^+bW^-\bar{b}$ , with  $H^+ \rightarrow \tau^+\nu_\tau$  (or the

corresponding charge-conjugate particles) could give rise to differences with respect to the standard model (SM) prediction of the number of  $t\bar{t}$  events with a  $\tau$  lepton [6]. The present measurement is based on data collected by the CMS experiment in pp collisions at  $\sqrt{s} = 8$  TeV corresponding to an integrated luminosity of  $19.6 \text{ fb}^{-1}$ . The relative accuracy of this measurement improves over previous results [7–11], thanks to the inclusion of additional data and improved analysis techniques.

The CMS detector is briefly introduced in Section 2, followed by details of the simulated samples in Section 3, and a brief description of the event reconstruction and event selection in Section 4. The descriptions of the background determination and the systematic uncertainties are given in Sections 5 and 6, respectively. The measurement of the cross section is discussed in Section 7, and the results are summarised in Section 8.

## 2. The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter and 13 m in length, providing a magnetic field of 3.8 T. Within the superconducting solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter, and a brass/scintillator hadron calorimeter, each composed of a barrel and two endcap sections. The calorimetry provides high-resolution energy and direction measurements of electrons and hadronic jets. Muons are identified using gas-ionisation detectors embedded in the steel flux-return

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yoke outside the solenoid. Extensive forward calorimetry complements the coverage provided by the barrel and endcap detectors. The CMS experiment uses a right-handed coordinate system, with the origin at the nominal interaction point, the  $x$  axis pointing to the centre of the LHC ring, the  $y$  axis pointing up (perpendicular to the LHC plane), and the  $z$  axis along the anticlockwise-beam direction. The polar angle  $\theta$  is measured from the positive  $z$  axis and the azimuthal angle  $\varphi$  is measured in the  $x$ - $y$  plane. Charged particle trajectories are measured covering  $0 < \varphi \leq 2\pi$  in azimuth and  $|\eta| < 2.5$ , where the pseudorapidity  $\eta$  is defined as  $\eta = -\ln[\tan(\theta/2)]$ . The detector is nearly hermetic, allowing for energy balance measurements in the plane transverse to the beam directions. A two-level trigger system selects the most interesting proton–proton collision events for use in physics analyses. A more detailed description of the CMS detector can be found elsewhere [12].

### 3. Data and simulation samples

Events are selected online by a trigger requiring a single isolated electron (muon) with transverse momentum  $p_T > 27$  (24) GeV and  $|\eta| < 2.5$  (2.1).

This measurement makes use of simulated samples of  $t\bar{t}$  events as well as other processes that mimic the  $\ell\tau_h$  decay signature. These samples are used to optimise the event selection, to calculate the acceptance for  $t\bar{t}$  events, and to estimate some of the backgrounds in the analysis.

The signal acceptance and  $t\bar{t}$  dilepton background are evaluated using a version of MADGRAPH which includes the effects of spin correlations [13,14]. The number of expected  $t\bar{t}$  events is estimated with the next-to-next-to-leading-order (NNLO) SM cross section of  $251.7^{+6.3}_{-8.6}$  (scale)  $\pm 6.5$  (PDF) pb [15–19] for a top-quark mass of 172.5 GeV, where the first uncertainty is due to renormalisation and factorisation scales, and the second is due to the choice of parton distribution functions (PDFs). The generated events are subsequently processed with PYTHIA 6.426 [20] which performs the hadronisation of partons. Soft radiation is matched to the contributions from direct emissions accounted for in the matrix-element calculations using the  $k_T$ -MLM approach [21]. The  $\tau$  lepton decays are simulated using TAUOLA 27.121.5 [22], which accounts for the  $\tau$ -lepton polarisation.

The samples containing  $W$  + jet and  $Z$  + jet events are simulated using the MADGRAPH 5.1.3.30 event generator [23]. The electroweak production of single top quarks is considered as a background process and is simulated with POWHEG 1.0, r1380 [24–28]. The diboson production processes  $WW$ ,  $WZ$ , and  $ZZ$  are generated with PYTHIA 6.424. In each case, the PYTHIA parameters for the underlying event are set according to the Z2\* tune [29], which uses the CTEQ6L PDFs [30].

Simulated events are processed using the full CMS detector simulation based on GEANT4 [31,32], followed by a detailed trigger emulation and event reconstruction. For both signal and background events, additional pp interactions (pileup) in the same or nearby bunch crossings are simulated with PYTHIA and superimposed on the hard collision, using a pileup multiplicity distribution that reflects the luminosity profile of the analysed data.

### 4. Event selection

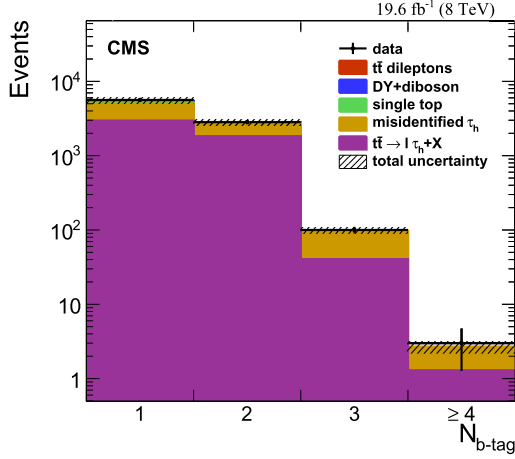
Events are reconstructed with the particle-flow (PF) algorithm [33,34], which combines information from all sub-detectors to identify and reconstruct individual electrons, muons, photons, charged and neutral hadrons. The primary collision vertex is chosen as the reconstructed vertex with the largest  $\sum p_T^2$  of the

associated tracks. Electrons are identified with a multivariate discriminant combining several quantities describing the track quality, the shape of the energy deposits in the electromagnetic calorimeter, and the compatibility of the measurements from the tracker and the electromagnetic calorimeter [35], and are reconstructed with an average efficiency of approximately 95%. Muons are identified with additional requirements on the quality of the track reconstruction and on the number of measurements in the tracker and the muon systems [36], and are reconstructed with an average efficiency of approximately 96%. Charged and neutral particles provide the input to the anti- $k_T$  jet clustering algorithm with a distance parameter of 0.5 [37]. The jet momentum is determined from the vector sum of particle momenta in the jet. After jet energies are corrected for additional pileup contributions and for detector effects, they are found in simulations to be within 5–10% of the actual jet momentum [38]. The missing transverse energy  $E_T^{\text{miss}}$  is calculated as the magnitude of the vector sum of momenta from all reconstructed particles in the plane transverse to the beam.

In addition, higher-level observables such as b-tagging discriminators and lepton isolation variables are used. The lepton relative isolation is defined as the transverse energy contributions deposited by charged hadrons ( $E_{T,\text{ch}}$ ), neutral hadrons ( $E_{T,\text{nh}}$ ), and photons ( $E_{T,\text{ph}}$ ) in a cone of radius  $R = \sqrt{(\Delta\varphi)^2 + (\Delta\eta)^2} = 0.4$  centred on the lepton candidate track, relative to the lepton's transverse momentum ( $p_T$ ),  $I_{\text{rel}} = (E_{T,\text{ch}} + E_{T,\text{nh}} + E_{T,\text{ph}})/p_T$ . An electron (muon) candidate is considered to be non-isolated and is rejected if  $I_{\text{rel}} > 0.1$  ( $> 0.12$ ).

The hadronic products of the  $\tau$ -lepton decay are reconstructed using a jet as the initial seed, and are then classified as having one or three charged hadrons with the “hadron-plus-strips” algorithm [39,40]. In the “hadron-plus-strips” algorithm, calorimeter energy deposits clustered along strips in the  $\varphi$  direction are used for neutral pion identification. Then, the decay modes, four-momenta, and isolation quantities of the  $\tau_h$  are determined, and the following categories are considered: single hadron, hadron plus a strip, hadron plus two strips, and three hadrons. These categories together encompass approximately 95% of hadronic  $\tau$ -lepton decays. The sum of the charged hadron charges provides the  $\tau_h$  charge. The  $\tau_h$ -jet momentum is required to match the direction of the original jet within a maximum distance  $R = 0.1$ . Isolation criteria require that there be no additional charged hadrons with  $p_T > 1.0$  GeV or photons with transverse energy  $E_T > 1.5$  GeV within a cone of size  $R = 0.5$  around the direction of the  $\tau_h$  jet. Electrons and muons misidentified as  $\tau_h$  are suppressed using algorithms that combine information from the tracker, calorimeters, and muon detectors [12]. The  $\tau_h$  identification efficiency is defined as the ratio of the number of selected  $\tau_h$  candidates divided by the number of hadronic  $\tau$ -lepton decays in  $t\bar{t}$  events; the ratio depends on  $p_T$  and  $\eta$  of the  $\tau_h$ , and is on average 50% for  $p_T^{\tau_h} > 20$  GeV, with a probability of approximately 1% for generic jets to be misidentified as a  $\tau_h$  jet.

The combined secondary vertex (CSV) algorithm [41] is used to identify jets originating from the hadronisation of b quarks. The algorithm combines the information about track impact parameters and secondary vertices within jets into a likelihood discriminant to provide separation between b jets and jets originating from light quarks, gluons, or charm quarks. The output of this CSV discriminant has values between zero and one; a jet with a CSV value above a certain threshold is referred to as being “b tagged”. We choose a working point where the b-tagging efficiency is approximately 60%, as measured in a data sample of events enriched with jets from semileptonic b-hadron decays. The misidentification rate of light-flavour jets is estimated from inclusive jet studies and is measured to be about 0.1% for jets with  $p_T > 30$  GeV.



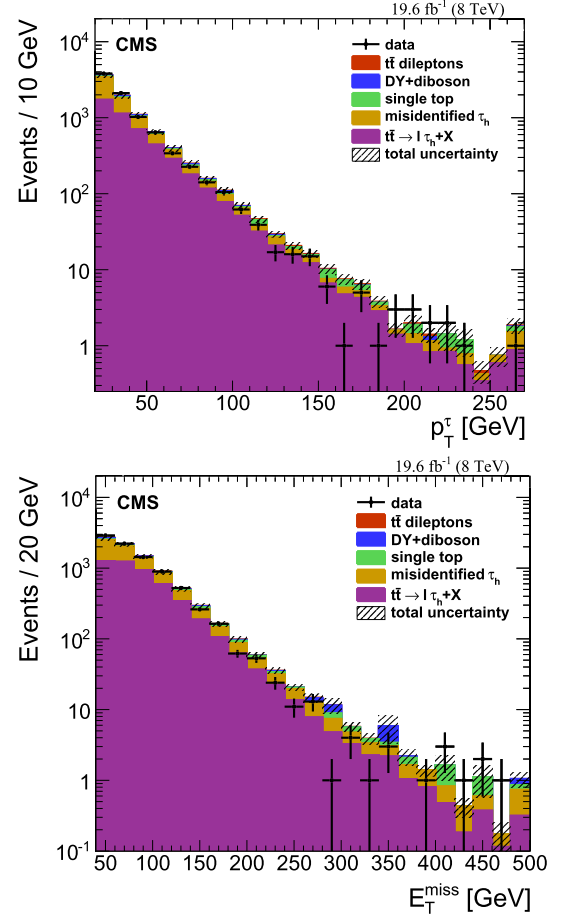
**Fig. 1.** The b-tagged jet multiplicity after the full event selection. The simulated contributions are normalised to the SM predicted values. The hatched area shows the total uncertainty.

Events are preselected by requiring exactly one isolated electron (muon) with transverse momentum  $p_T > 35$  (30) GeV and  $|\eta| < 2.5$  (2.1), at least two jets with  $p_T > 30$  GeV, and one additional jet with  $p_T > 20$  GeV. The selected jets must be within  $|\eta| < 2.4$ . The electron or muon is required to be separated from any jet in the  $(\eta, \varphi)$  plane by a distance  $R > 0.4$ . Events with any additional loosely isolated,  $I_{\text{rel}} < 0.2$ , electron (muon) of  $p_T > 15$  (10) GeV are rejected. Further event selection requirements include  $E_T^{\text{miss}} > 40$  GeV and only one  $\tau_h$  with  $p_T > 20$  GeV and  $|\eta| < 2.4$ . The  $\tau_h$  and the lepton are required to have electric charges of opposite sign (OS). At least one of the jets is required to be identified as originating from b-quark hadronisation (b-tagged).

Fig. 1 shows, for the sum of the  $e\tau_h$  and  $\mu\tau_h$  final states, a comparison between data and simulation of the number of b-tagged jets in each event  $N_{b\text{-tag}}$  after all the selection criteria have been applied. The distributions of the  $\tau_h$   $p_T$  and  $E_T^{\text{miss}}$  after the final event selection are shown in the top and bottom panels of Fig. 2, respectively. The distributions show agreement between the observed numbers of events and the expected numbers of signal and background events obtained from the simulated distributions normalised to the integrated luminosity of the selected data sample.

Following the final selection, additional kinematic features of the  $t\bar{t}$  events are studied to evaluate the agreement between the observed data and the predicted sum of signal and background. For each event, two invariant mass combinations are reconstructed by pairing the  $\tau_h$  with the two candidate b-jets: (1) in events with two or more b-tagged jets, the two combinations are based on the two b-tagged jets with the highest value of the discriminator; (2) in events with one b-tagged jet, this is used for the first combination, while the non-b-tagged jet with the highest  $p_T$  is used to form the second combination. For the two combinations, the invariant mass with the lowest value is shown in Fig. 3 (top), for the  $e\tau_h$  and  $\mu\tau_h$  channels combined.

For each event, the top-quark mass  $m_{\text{top}}$  is reconstructed using the KINb algorithm [42,43]. Due to the multiple neutrinos in the event, the reconstruction of  $m_{\text{top}}$  leads to an underconstrained system. The KINb algorithm applies constraints on the W boson mass, the mass difference between the top and anti-top quark, and the longitudinal momentum of the  $t\bar{t}$  system. For each event, solutions to the kinematic equations are evaluated, varying the jet momenta and the direction of  $E_T^{\text{miss}}$  within their resolutions. For each set of variations and each lepton–jet combination, the kinematic equations allow up to four solutions; the one with the lowest  $t\bar{t}$  invariant mass is accepted if the mass difference between the two



**Fig. 2.** Distribution of the  $\tau_h$   $p_T$  (top) and  $E_T^{\text{miss}}$  (bottom) after the full event selection, for the  $e\tau_h$  and  $\mu\tau_h$  channels combined. The simulated contributions are normalised to the SM predicted values. The hatched area shows the total uncertainty. The last bins include the overflow events.

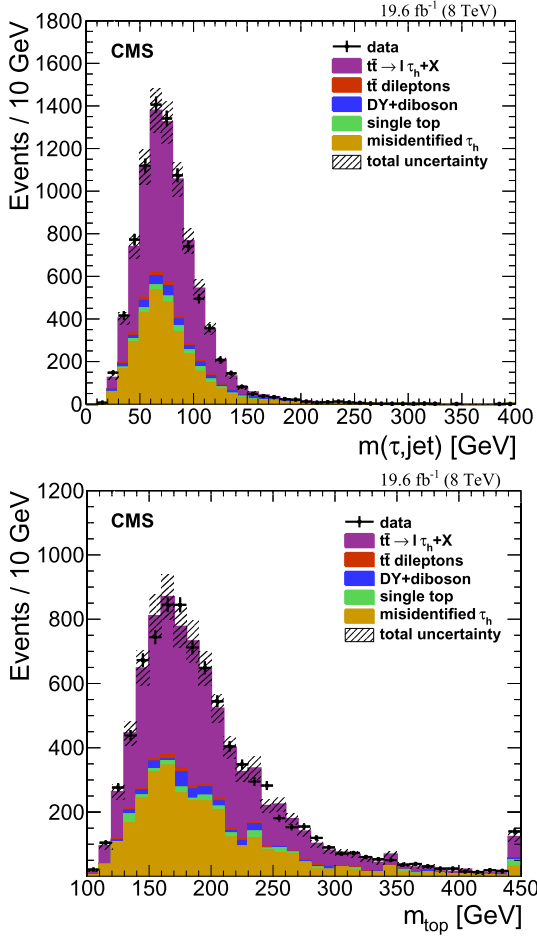
top quarks is less than 3 GeV. For each event, the accepted solutions corresponding to the two possible lepton–jet combinations are counted and the combination with the largest number of solutions is chosen and  $m_{\text{top}}$  is obtained by fitting the peak of this distribution. The events in which solutions are found are shown in Fig. 3 (bottom). Data are in agreement with the expected sum of signal and background events.

## 5. Background estimate

The main background (misidentified  $\tau_h$ ) comes from events with one lepton (electron or muon), significant  $E_T^{\text{miss}}$ , and three or more jets, where one jet is misidentified as a  $\tau_h$  jet [6]. The dominant source is  $t\bar{t}$  lepton + jet events. The misidentified  $\tau_h$  background accounts also for events with W bosons produced in association with jets, either genuine W + jet or single-top-quark production, and for QCD multijet events. In order to estimate this background from data, the misidentification probability  $w(\text{jet} \rightarrow \tau_h)$  is parameterised as a function of the jet  $p_T$ ,  $\eta$ , and width ( $R_{\text{jet}}$ ). The quantity  $R_{\text{jet}}$  is defined as  $\sqrt{\sigma_\eta^2 + \sigma_\varphi^2}$ , where  $\sigma_\eta$  ( $\sigma_\varphi$ ) expresses the extent in  $\eta$  ( $\varphi$ ) of the jet cluster [38].

The probability  $w(\text{jet} \rightarrow \tau_h)$  is evaluated from two control samples:

- $w_{W+\text{jets}}$ : from a W + jet event sample, selected by requiring one isolated muon with  $p_T > 20$  GeV and  $|\eta| < 2.1$ , and at least one jet with  $p_T > 20$  GeV and  $|\eta| < 2.4$ ;



**Fig. 3.** (Top) Minimum invariant mass reconstructed by pairing the  $\tau_h$  with either a b-tagged jet or with the highest  $p_T$  non-b-tagged jet, as described in the text. (Bottom) Distribution of the reconstructed top-quark mass  $m_{\text{top}}$  for the  $\ell\tau_h$  candidate events after the full event selection. Data (points) are compared with the sum of signal and background yields, for the  $e\tau_h$  and  $\mu\tau_h$  channels combined. The simulated contributions are normalised to the SM predicted values. The hatched area shows the total uncertainty. The last bins include the overflow events.

- $w_{\text{QCD}}$ : from a QCD multijet sample, triggered by one jet with  $p_T > 40$  GeV, selected by requiring events to have at least two jets with  $p_T > 20$  GeV and  $|\eta| < 2.4$ , where the triggering jet is removed from the misidentification rate calculation to avoid a trigger bias.

Both probabilities are evaluated in simulated events as well as in data, with good agreement found between the results from simulation and data [39].

The number of events containing misidentified  $\tau_h$  candidates is then determined as

$$N^{\text{misid}} = \sum_i^M \sum_j^m w_i^j(\text{jet} \rightarrow \tau) - N^{\text{other}}, \quad (1)$$

where  $j$  is the jet index of event  $i$ , and  $m$  is the number of jets in each event and  $M$  is the total number of events. The quantity  $N^{\text{other}}$  is the expected  $\simeq 20\%$  contamination from signal and other processes to the misidentified background as estimated from simulated samples. The value of  $N^{\text{other}}$  is evaluated by applying the procedure described above to simulated events of  $Z/\gamma^* \rightarrow \tau\tau$ , single-top-quark production, diboson production, and the  $t\bar{t}$  processes included in the misidentified  $\tau_h$  background estimation.

Jets in QCD multijet events originate mainly from gluons, while in  $W + \text{jet}$  events they are predominantly from quarks. The quark

**Table 1**

List of systematic uncertainties in the cross section measurement, and their combination. Lepton reconstruction uncertainties are uncorrelated, while all other uncertainties are assumed 100% correlated.

| Source   | Uncertainty [%] |             |          |
|--|-----------------|-------------|----------|
|  | $e\tau_h$       | $\mu\tau_h$ | Combined |
| <i>Experimental uncertainties:</i>                           |                 |             |          |
| $\tau_h$ jet identification                                  | 6.0             | 6.0         | 6.0      |
| $\tau_h$ misidentification background                        | 4.3             | 4.3         | 4.3      |
| $\tau_h$ energy scale  | 2.4             | 2.5         | 2.5      |
| b-jet tagging, jet misidentification                         | 1.6             | 1.6         | 1.6      |
| jet energy scale, jet energy resolution, $E_T^{\text{miss}}$ | 1.9             | 1.9         | 1.9      |
| lepton reconstruction  | 0.8             | 0.6         | 0.5      |
| other backgrounds  | 0.6             | 0.7         | 0.7      |
| luminosity   | 2.6             | 2.6         | 2.6      |
| <i>Theoretical uncertainties:</i>                            |                 |             |          |
| matrix element–parton shower matching                        | 1.7             | 1.3         | 1.5      |
| factorisation/renormalisation scale                          | 2.9             | 2.9         | 2.9      |
| generator  | 1.5             | 1.5         | 1.5      |
| hadronisation  | 1.7             | 1.7         | 1.7      |
| top-quark $p_T$ modelling                                    | 0.7             | 0.5         | 0.6      |
| parton distribution functions                                | 0.8             | 0.7         | 0.7      |
| total systematic uncertainty                                 | 9.6             | 9.5         | 9.5      |

and gluon composition in the misidentified  $\tau_h$  events lies between these two control samples. As  $w_{\text{QCD}} < w_{W+\text{jets}}$ , the actual  $N^{\text{misid}}$  value is under- (over-) estimated by applying the  $w_{\text{QCD}}$  ( $w_{W+\text{jets}}$ ) probability. We determine from data the rate for the misidentification of a jet to be identified as a  $\tau_h$ , and from simulation the quark/gluon composition in the  $W + \text{jet}$  and multijet samples. From these quantities we derive the following combination:

$$\langle N^{\text{misid}} \rangle = SF_{W+\text{jet}} \times N_{W+\text{jet}}^{\text{misid}} + SF_{\text{QCD}} \times N_{\text{QCD}}^{\text{misid}}, \quad (2)$$

where the misidentification rates, extracted from the data control samples discussed above, are combined with the scale factors  $SF$ s determined from the set of equations describing the quark/gluon composition of the samples:  $SF_{\text{QCD}} = 0.83$  and  $SF_{W+\text{jet}} = 0.17$ . The corresponding systematic uncertainty is obtained from Eq. (2) by weighting the relative deviations of  $N_{W+\text{jet}}^{\text{misid}}$  and  $N_{\text{QCD}}^{\text{misid}}$  from  $\langle N^{\text{misid}} \rangle$  with the related scale factors. This results in an uncertainty of 7% for both  $e\tau_h$  and  $\mu\tau_h$  channels.

The efficiency of the OS requirement  $\varepsilon_{\text{OS}}$  is determined from simulated lepton + jet  $t\bar{t}$  events and is applied in order to obtain the misidentified  $\tau_h$  background after the final event selection  $N_{\text{OS}}^{\text{misid}}$ , where  $N_{\text{OS}}^{\text{misid}} = \varepsilon_{\text{OS}} \cdot N^{\text{misid}}$ . We find values of  $\varepsilon_{\text{OS}} = 0.729 \pm 0.002$  (stat)  $\pm 0.004$  (syst) for the  $e\tau_h$  selection and  $\varepsilon_{\text{OS}} = 0.731 \pm 0.002$  (stat)  $\pm 0.003$  (syst) for the  $\mu\tau_h$  selection, where all sources of systematic uncertainty are accounted for in the modelling of the simulated  $t\bar{t}$  lepton + jet events.

## 6. Systematic uncertainties

Several sources of systematic uncertainty are considered and listed in Table 1. They are related both to the signal reconstruction efficiency, background determination, and luminosity measurement (Experimental uncertainties) and to the theoretical assumptions on the  $t\bar{t}$  production (Theoretical uncertainties). In Table 1 and in what follows, relative values refer to the cross section uncertainty unless explicitly stated otherwise.

### 6.1. Experimental uncertainties

Regarding the  $\tau_h$  reconstruction, the uncertainty associated with the identification efficiency amounts to 6%, while the contribution relative to the  $\tau_h$  jet energy scale is 2.4% (2.5%) for the  $e\tau_h$  ( $\mu\tau_h$ ) channel, as estimated by varying the  $p_T$  of the  $\tau_h$  jet



by 3% [39,40]. The uncertainty in the  $\tau_h$  identification efficiency includes the uncertainty in charge determination which is estimated to be smaller than 1%. The uncertainty related to the misidentified  $\tau_h$  background process, discussed in Section 5, is obtained by propagating the 7% uncertainty on  $\langle N^{\text{misid}} \rangle$  to the cross section determination and results in 4.3% for both channels. It also includes the uncertainty in the OS efficiency determination.

The reconstruction of a light flavour jet as a b quark is defined as mistagging. The uncertainty due to b (mis)tagging is estimated to reflect the data-to-simulation scale factors and corresponding uncertainties for b-tagging and mistagging efficiencies [41]. When propagated to the cross section measurement, they amount to 1.6% for both  $e\tau_h$  and  $\mu\tau_h$  channels.

The jet energy scale (JES) uncertainty is estimated [38] by varying the jet energy within the  $p_T$ - and  $\eta$ -dependent JES uncertainties per jet, and taking into account the uncertainty due to pileup and parton flavour. The jet energy resolution (JER) is estimated by smearing the jet energy in simulation within the  $\eta$ -dependent JER uncertainties per jet. The JES and JER uncertainties are propagated in order to estimate the uncertainty of the  $E_T^{\text{miss}}$  scale. In addition, modelling of the  $E_T^{\text{miss}}$  component, which is not clustered in jets, is also considered. The resulting uncertainty from propagating these effects to the cross section measurement is 1.9% for both the  $e\tau_h$  and  $\mu\tau_h$  channels.

Uncertainties due to trigger, lepton identification, isolation, and lepton energy scale are calculated from independent samples with a “tag-and-probe” method [35,36], and yield 0.8% (0.6%) for the  $e\tau_h$  ( $\mu\tau_h$ ) channel.

An overall 0.6% (0.7%) uncertainty for the  $e\tau_h$  ( $\mu\tau_h$ ) channel is due to other minor backgrounds, accounting for the uncertainties related to the theoretical cross sections, JES, and b-tagging in these simulated samples, and the  $\ell \rightarrow \tau_h$  ( $\ell = e, \mu$ ) misidentification in the  $Z/\gamma^* \rightarrow \ell^+\ell^-$  and  $t\bar{t}$  dilepton processes.

Finally, the integrated luminosity is known with 2.6% accuracy [44].

## 6.2. Theoretical uncertainties

The theoretical uncertainty due to the matrix element (ME) and parton shower (PS) matching is estimated by varying up and down by a factor of two the threshold between jet production at the ME level and via PS, and it results in 1.7% (1.3%) for the  $e\tau_h$  ( $\mu\tau_h$ ) channel.

The modelling uncertainty in the signal acceptance due to the factorisation and renormalisation scale choices is estimated by varying them simultaneously up and down by a factor of two from the nominal value equal to the  $Q^2$  in the event, with an uncertainty of 2.9% found for both channels.

The uncertainty due to the choice of the generator is estimated as the relative difference between the acceptances evaluated with MADGRAPH and POWHEG [24–26,45] after the full event selection and results in 1.5%. In a similar way, the uncertainty in the hadronisation scheme is evaluated from the relative differences between the acceptances from POWHEG + PYTHIA and POWHEG + HERWIG samples, estimated prior to the b-tagging or  $\tau_h$  jet requirement, resulting in a 1.7% uncertainty.

We consider the uncertainty related to the top-quark  $p_T$  scale modelling by varying the top-quark  $p_T$  spectrum and evaluating the change in the signal acceptance, resulting in 0.6%, and the uncertainty related to the PDF variations following the PDF4LHC prescriptions [17], resulting in 0.7%.

## 7. Cross section measurement

The number of expected signal and background events as well as the number of observed events after all selections are

**Table 2**

Number of expected events for signal (assuming  $m_{\text{top}} = 172.5$  GeV) and backgrounds. The background from misidentified  $\tau_h$  is estimated from data, while the other backgrounds are estimated from simulation. Statistical and systematic uncertainties are shown.

| Source  | $e\tau_h$            | $\mu\tau_h$           |
|---|----------------------|-----------------------|
| misidentified $\tau_h$                                      | $1341 \pm 3 \pm 94$  | $1653 \pm 3 \pm 116$  |
| $t\bar{t} \rightarrow (\ell\nu_\ell)(\ell\nu_\ell)b\bar{b}$ | $55 \pm 1 \pm 3$     | $68 \pm 2 \pm 4$      |
| $Z/\gamma^* \rightarrow ee, \mu\mu$                         | $11 \pm 5 \pm 5$     | $12 \pm 5 \pm 5$      |
| $Z/\gamma^* \rightarrow \tau\tau$                           | $85 \pm 14 \pm 8$    | $166 \pm 20 \pm 18$   |
| single top quark  | $104 \pm 7 \pm 9$    | $133 \pm 8 \pm 10$    |
| dibosons  | $15 \pm 1 \pm 1$     | $19 \pm 1 \pm 1$      |
| total expected background                                   | $1611 \pm 17 \pm 95$ | $2051 \pm 22 \pm 118$ |
| expected signal yield                                       | $2134 \pm 9 \pm 170$ | $2632 \pm 11 \pm 212$ |
| data  | 3779                 | 4767                  |

summarised in Table 2. The statistical and systematic uncertainties are also shown. The  $t\bar{t}$  production cross section measured from  $\tau$  dilepton events is  $\sigma_{t\bar{t}} = (N - B)/(L \cdot A_{\text{tot}})$ , where  $N$  is the number of observed candidate events,  $B$  is the estimate of the background and  $L$  is the integrated luminosity. The total acceptance  $A_{\text{tot}}$  is the product of the branching fractions, geometrical and kinematic acceptance, trigger, lepton identification, and the overall reconstruction efficiency. It is evaluated with respect to the inclusive  $t\bar{t}$  sample. After the OS requirement and assuming a top-quark mass  $m_{\text{top}} = 172.5$  GeV, we obtain:

$$A_{\text{tot}}(e\tau_h) = 0.04333 \pm 0.00017 (\text{stat}) \pm 0.00300 (\text{syst})\%;$$

$$A_{\text{tot}}(\mu\tau_h) = 0.05370 \pm 0.00021 (\text{stat}) \pm 0.00376 (\text{syst})\%.$$

The statistical uncertainties are due to the limited number of simulated events and the systematic uncertainties are estimated by accounting for all sources listed in Table 1. The statistical and systematic uncertainties listed in Table 2 are propagated to the final cross section measurements:

$$\sigma_{t\bar{t}}(e\tau_h) = 255 \pm 4 (\text{stat}) \pm 24 (\text{syst}) \pm 7 (\text{lumi}) \text{ pb};$$

$$\sigma_{t\bar{t}}(\mu\tau_h) = 258 \pm 4 (\text{stat}) \pm 24 (\text{syst}) \pm 7 (\text{lumi}) \text{ pb}.$$

The BLUE method [46] is used to combine the cross section measurements in the  $e\tau_h$  and  $\mu\tau_h$  channels, yielding weights of 0.47 and 0.53, respectively. Lepton reconstruction uncertainties are uncorrelated, while all other uncertainties are assumed 100% correlated. With this method we obtain a combined result of  $\sigma_{t\bar{t}} = 257 \pm 3 (\text{stat}) \pm 24 (\text{syst}) \pm 7 (\text{lumi}) \text{ pb}$ , in agreement with the NNLO expectation of  $251.7^{+6.3}_{-8.6} (\text{scales}) \pm 6.5 (\text{PDF}) \text{ pb}$ . Following the most recent conventions for the treatment of PDF and scale uncertainties the same calculation yields  $252.9^{+6.4}_{-8.6} (\text{scale}) \pm 11.7 (\text{PDF} + \alpha_s) \text{ pb}$  [15–19]. The dependence on the top-quark mass has been studied for the range 160–185 GeV and is well described by a linear variation. If we adjust our result to the current world average value of 173.3 GeV [47], we obtain a cross section that is lower by 3.1 pb.

## 8. Summary

A measurement of the  $t\bar{t}$  production cross section in the channel  $t\bar{t} \rightarrow (\ell\nu_\ell)(\tau\nu_\tau)b\bar{b}$  is presented, where  $\ell$  is an electron or a muon, and the  $\tau$  lepton is reconstructed through its hadronic decays. The data sample corresponds to an integrated luminosity of  $19.6 \text{ fb}^{-1}$  collected in proton–proton collisions at  $\sqrt{s} = 8 \text{ TeV}$ . Events are selected by requiring the presence of one isolated electron or muon, two or more jets (at least one of which is b-tagged), significant missing transverse energy, and one  $\tau$ . The

largest background contribution is estimated from data and consists of  $t\bar{t}$  events with one W boson decaying into jets, where one jet is misidentified as a  $\tau$ . The measured cross section is  $\sigma_{t\bar{t}} = 257 \pm 3$  (stat)  $\pm 24$  (syst)  $\pm 7$  (lumi) pb for a top-quark mass of 172.5 GeV. This measurement improves over previous results in this decay channel, and it is in good agreement with the standard model expectation and other measurements of the  $t\bar{t}$  cross section at the same centre-of-mass energy.

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